One of the primary objectives of the North American Die Casting Association is to provide technical information for the die casting industry. For many years, technical standards, technical education courses, and seminars have been provided by NADCA for the industry. Shot system components are one part of the die casting system that is often not given proper technical evaluation. It is the purpose of this users’ guide to provide guidelines for the design, use, and maintenance of these components to help improve the technical capability of die casters.

Introduction

There are two basic types of die casting machines. These are the cold chamber machine and the hot chamber machine. Cold chamber machines are used for casting alloys (such as aluminum, magnesium and brass) that would eventually dissolve the working parts of the machine if those parts of the machine were to be permanently submerged in the bath of molten metal. Hot chamber machines are used for casting alloys (such as zinc, lead and sometimes magnesium) that will not dissolve the metal injection components of the machine when they are permanently submerged in the bath of molten metal.

The difference between hot and cold chamber machines is essentially in the configurations of their metal injection systems. The two shot systems are shown in Figures 1 and 2. The cold chamber shot system components, the topic of this users’ guide, are utilized to push the molten metal through the cold chamber and into the die cavity.

Throughout this users’ guide, the important factors for the successful operation of cold chamber metal injection system components are discussed. These components include the cold chamber or shot sleeve, the plunger tip or shot tip, the shot cylinder and the plunger rod. These components provide motion and energy to the shot tip, which is in direct contact with the molten metal, and can directly affect the process by which castings are produced. Following this introduction, the next section will discuss the various components of the cold chamber metal injection system. Later in this guide is a discussion of operating guidelines for the injection system. Finally, some industry examples are presented, where the application of shot system components has been used to improve die casting operations.
Chapter 1

The Injection System

The purpose of the injection system, or shot system, of the die casting machine is to inject the molten metal into the die. It is mounted on the front plate of the machine by a C-frame (or similar mechanism) as shown in Figure 3. The C-frame maintains the alignment of the system, and also facilitates changing the height of the shot sleeve in those machines with alternate shot position capability.

The main components of the shot system are:

1. The cold chamber or shot sleeve
2. The plunger tip or shot tip
3. The shot cylinder
4. The plunger rod

One of the primary mechanical requirements of the shot system is to provide good alignment between the plunger tip and the cold chamber. Misalignment will result in a “drag” on the plunger tip which will affect the plunger speed. A hydraulic cylinder drives the plunger tip. The plunger tip is connected to a plunger rod which is connected to the cylinder rod with a coupling as shown in Figure 3. The function of the shot system is to inject the molten metal into the die under the proper conditions. These conditions involve precise control of the movement of, and the force on, the shot tip. Each phase of the shot itself and the transition from one phase to another are determined by engineering calculations for the particular casting to be made. The smooth and repeatable operation of the shot system is essential to provide the proper velocities and pressure rise times required for good die filling and quality castings. Each component of the injection system will be discussed individually, but the key to successful operation is that these components function as a system. Each component is critical to the success of the die casting operation.

The Shot Sleeve

Introduction

The primary function of a shot sleeve is to receive and hold the molten metal after ladling. It also provides a pressure chamber to contain the metal during injection and intensification. The quality of die castings will depend on many factors, including the ability of the shot sleeve to convey the molten alloy into the die cavity. It is essential that the inside of the shot sleeve be smooth, round, straight and uniform, to allow the appropriate velocities and pressure rise times required for precise die filling and intensification. The shot sleeve is exposed to extremely severe operating conditions, as during operation sleeve temperatures can approach 1,000 °F, the plunger can reach velocity of 6m/sec or more, and metal pressures can be as high as 25,000 psi. Therefore, it is essential that shot sleeves be fabricated correctly and utilized in ways that optimize die casting process parameters. In addition, the goal for most (all) die casters is to maximize the life of their sleeve while controlling costs.

The shot sleeve inside diameter is one of the most critical parameters of the cold chamber die casting process. The ID determines the metal pressure, metal injection velocities and flow rates, cavity fill times and the percentage of sleeve fill. The IDs should be determined for each die and die casting machine combination by using a process analysis such as PQ and a finite element flow analysis. This section of this users' guide will examine the operation and design of shot sleeve, describes materials used to produce sleeves, and describe methods to optimize their performance.

Operation and Design

A typical shot sleeve design is shown in Figure 4. Most commonly the sleeves are fabricated in one piece, contain a flange to hold the sleeve in position between the fixed die half and the machine platen, and a pour hole for introduction of the liquid metal. One-piece sleeves can, however, be designed with multiple flanges to accommodate more than one die fixed thickness, or with a screw ring on the OD which allows the die caster...
to vary the ring length for different die thicknesses, by simply screwing the ring forwards or backwards.

Figure 4: Photograph of a one-piece shot sleeve

Two-piece shot sleeve designs are also common. A two-piece sleeve is shown in Figure 5, which is made up of two cylinders, the bushing and the sleeve. The bushing is contained in the fixed die half and is dedicated to a specific die. The sleeve is a cylinder that matches the bushing’s ID, is located within the fixed platen, and contains the pour hole. This style of shot sleeve can minimize setup times since the sleeve does not have to be changed when a die with a different thickness of fixed side is put in the machine. There is also the cost savings of having to replace only one part of the two-piece sleeve, if the sleeve fails due to erosion under the pour hole. One problem with this type of two-piece sleeve is that the alignment of the two halves is critical. If the alignment of the bushing and sleeve ID’s is improper, accelerated tip wear will occur, which can only be prevented if tight dimensional tolerances are held.

Figure 5: Two-piece sleeve design

There is also a second style of two-piece sleeve that can be used. In this design, shown in Figure 6, the section of the sleeve containing the pour hole is separate, allowing just that section to be replaced when severe erosion under the pour hole occurs.

Figure 6: Two-piece sleeve design

Failure of Sleeves

Shot sleeves normally fail from one of the following five reasons\(^{3-5}\):

- Erosion under the pour hole
- Soldering of the aluminum to the sleeve
- Wear and scoring on the internal surface
- Gross or large scale cracking leading to catastrophic failure
- Thermal fatigue producing small surface cracks (heat checking) on the inside surface

These are each described in more detail below.

Erosion – Erosion under the pour hole (Figure 7) occurs as the liquid aluminum poured into the steel dissolves a small amount of the steel shot sleeve on each shot. As erosion tends to occur faster when the steel substrate become hotter, erosion rates are increased with higher production rates and higher levels of melt superheat, as there in not sufficient time between shots for the sleeve to cool\(^{5}\). Sobol\(^{3}\) points out that the use of automatic ladling can also result in an increase in the amount of erosion under the pour hole, as the liquid metal will hit the same spot on inside of the sleeve shot-after-shot.
Soldering – Soldering occurs when a thin layer of aluminum become permanently welded to the inside diameter of the sleeve. This can cause severe scoring, sticking and wear of the plunger tip\(^{(3)}\).

Wear – Wear and scoring observed on the inside diameter of the sleeve is shown in Figure 8. Although this will normally occur over time, it can be worsened from the distortion of the sleeve that occurs due to differential heating. As shown in Figure 9, typically the bottom of the sleeve is hotter than the top, and other hot areas of the sleeve include immediately under the pour hole and at the front of the sleeve where the biscuit solidifies. These temperature differences produce distortions of the sleeve, resulting in a bending of the sleeve along its length, as well as forcing the inner diameter out-of-round. Such distortions mean that the plunger tip will no longer move smoothly and easily along the sleeve, resulting in wear and scoring. This distortion will be described in more detail later in this users’ guide.

Gross Cracking – Gross cracking of sleeves can often occur due to problems with materials of construction (such as inferior steel) or from design issues. For example, Murphy\(^{(2)}\) suggests that, to prevent gross cracking, it is important to avoid or minimize abrupt changes in the diameter, notches and sharp corners in the sleeve design.

Heat Checking – The heat checking that occurs on the inside diameter of shot sleeves is similar in nature to that found on the cavity faces, and occurs from the cyclic heating and cooling of the sleeve each time the liquid metal is ladled into the sleeve.

Several publications provide recommendations for optimum wall thickness for shot sleeves, and a common rule-of-thumb is that the wall thickness should be at least one third of the inside diameter of the sleeve\(^{(8)}\). Sobol et al\(^{(4)}\) empirically developed a more detailed recommendation for wall thickness of shot sleeves based on the need to prevent gross cracking and minimize wear. This is reproduced in Table 1.

<table>
<thead>
<tr>
<th>ID</th>
<th>Cracking OD</th>
<th>Cracking Thickness</th>
<th>Wear OD</th>
<th>Wear Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>2.314</td>
<td>0.407</td>
<td>2.361</td>
<td>0.431</td>
</tr>
<tr>
<td>2.0</td>
<td>3.085</td>
<td>0.543</td>
<td>3.148</td>
<td>0.574</td>
</tr>
<tr>
<td>2.5</td>
<td>3.857</td>
<td>0.678</td>
<td>3.935</td>
<td>0.718</td>
</tr>
<tr>
<td>3.0</td>
<td>4.628</td>
<td>0.814</td>
<td>4.722</td>
<td>0.861</td>
</tr>
<tr>
<td>3.5</td>
<td>5.400</td>
<td>0.950</td>
<td>5.509</td>
<td>1.005</td>
</tr>
<tr>
<td>4.0</td>
<td>6.171</td>
<td>1.085</td>
<td>6.296</td>
<td>1.148</td>
</tr>
<tr>
<td>4.5</td>
<td>6.942</td>
<td>1.221</td>
<td>7.084</td>
<td>1.292</td>
</tr>
<tr>
<td>5.0</td>
<td>7.714</td>
<td>1.357</td>
<td>7.871</td>
<td>1.435</td>
</tr>
</tbody>
</table>

Table 1: Minimum H13 steel sleeve thickness to prevent cracking and minimize wear\(^{(4)}\)
Methods for maximizing the life of sleeves through decreasing failures are listed below\(^5\), and will be addressed in subsequent sections of this users’ guide:

- Increasing the wall thickness of the sleeve, to allow it to absorb more heat.
- Changing the material of construction
- Either cooling the underside of the sleeve, or preheating the upper surface of the sleeve, to minimize distortion.

Materials

Over the years a number of materials have been evaluated for shot sleeves, including cast irons, carbon steels, stainless steels, and nickel-based superalloys\(^6\), but today nearly all shot sleeves are fabricated from premium grade H13 steel. Similar to the H13 steel used to produce dies, H13 used to fabricate sleeves has to be heat treated to provide a suitable combination of toughness, and resistance to thermal fatigue, erosion and wear\(^3\). The heat treatment used is similar to that employed for die steels (outlined in detail in NADCA publication #229, “Special Quality Die Steel and Heat Treatment Acceptance Criteria for Die Casting Dies”). Although the heat treatment of the sleeve is normally performed by the supplier, it is worthwhile to briefly review the process here. Initially the sleeve is heated to the austenitizing temperature (close to 1885 °F), held for a short period and then rapidly cooled (quenched) at a rate of at least 50 °F/minute. A minimum of two tempering treatments at temperatures close to 1050 °F are then given, to achieve a target hardness of 46-48 HRC\(^3,9\).

Nitriding to increase the hardness of the inside surface of the shot sleeve has been shown to reduce erosion\(^3\). Schwam et al\(^6\) performed an accelerated bench-scale trial to characterize erosion under the pour hole, and the photographs in Figure 10 show the change in erosion between 600 shots and 2,200 shots. Quantitative information on the depth of erosion damage is reproduced in Figure 11. It is worth noting that the alloy used for this test was low-iron A356, and the pouring temperature was higher than normal, so the rate of erosion might be more severe than would be observed with regular die casting operations with conventional die casting alloys.

Figure 10: Pour hole erosion for a nitrided H13 steel shot sleeve\(^6\)

Schwam et al\(^6\) also examined the impact on erosion of placing hard coatings on the inside surface of sleeves. They used the physical vapor deposition (PVD) process to place a 10 µm thick layer of TiAlN on the inside diameter of an H13 shot sleeve. Photographs showing the level of erosion under the pour hole after 600 and 1,000 shots are shown in Figure 13, and as shown quantitatively in Figure 14, the rate of erosion of the PVD coated sleeve is significantly lower compared to a sleeve that was simply nitrided.

Figure 11: Depth of pour hole erosion for a nitrided H13 steel shot sleeve\(^6\)

Schwam et al\(^6\) also examined the mechanism of washout and soldering in H13 shot sleeves, and found it is similar to that observed for die casting cavities. As shown in Figure 12, the soldering in their nitrided H13 shot sleeve was found to initiate by formation of Al-Fe intermetallics at the aluminum-steel interface, while erosion occurred by iron dissolution into the molten aluminum.

Figure 12: Mechanism of washout and soldering in H13 shot sleeves\(^6\)
Figure 13: Erosion under the pour hole after 600 shots (left) and 1,000 shots (right) for a shot sleeve with a TiAlN PVD coating.(6)

Figure 14: Comparison of the depth of pour hole erosion for a nitrided H13 steel shot sleeve versus a shot sleeve given a TiAlN PVD coating.(6)

Another design of shot sleeves includes a copper jacket on the outside diameter of the sleeve.(10) The liquid metal does not contact the copper jacket, but the jacket is engineered to move heat from the hotter areas (under the pour hole and the biscuit end of the sleeve) and distribute it over the remainder of the sleeve.

Recently, materials other than H13 steel have been considered for shot sleeves, and this is especially true for some of the more extreme applications of die casting, such as vertical squeeze casting or the die casting of low-iron alloys. For example, the use of a titanium-based metal-matrix composite (Ti-MMC) has been reported by several organizations.(11-13) The Ti-MMC has a lower thermal conductivity than H13 steel, and so less heat is lost from the liquid metal to the shot sleeve during ladling, and the Ti-MMC also appears to better resist erosion and washing. For example, Abkowitz et al.(13) published a sleeve design that incorporates an internal liner fabricated from Ti-MMC, held in position within an H13 steel shot sleeve by H13 steel end caps (Figure 15). Abkowitz et al.(13) indicate that the Ti-MMC is a tough, wear-resistant material that better resists aluminum soldering. Early commercial applications were described for vertical squeeze casting, where shot sleeve life was reported to be extended from 20,000 shots (for steel sleeves) to 200,000 shots or more for the Ti-MMC. They also indicate that casters were able to reduce shot sleeve lubrication by 30%, and that plunger life was increased by 100%. Abkowitz et al.(13) report that these Ti-MMC sleeves are now starting to be used with horizontal die casting machines, especially with the more aggressive alloys, and sleeve life is reported to be extended by a factor of three(13). Properties of this Ti-MMC are compared with H13 steel in Table 2.

Table 2: Property comparison between titanium metal-matrix composite and H13 steel(13)

Donahue et al.(14) report on the initial testing of niobium liners inserted into steel sleeves. Niobium is one metal that does not appear to dissolve in liquid aluminum(15), and should therefore better resist erosion and soldering. This can be especially important when casting low-iron alloys such as 362, which tend to be very aggressive and intensify erosion under the pour hole.

A niobium sleeve liner is shown in Figure 16. The liner was fabricated from niobium sheet approximately 0.2 inches thick, which was wrapped around a mandrel and welded. A casting trial indicated that there was no washout under the pour hole, minimal wear to the liner, but that the plunger tip experienced a higher level of wear. Donahue et al.(14) also indicate that tip flash formed consistently, which they attributed to a loose clearance between the tip and the sleeve liner.

Temperature Profiles, Distortion and Cooling

For problem-free operation of the shot sleeve and plunger tip, it is important that the clearance between the shot sleeve and plunger tip be sleeve and tip correct, and that the sleeve and tip be correctly aligned. Alignment will be discussed in more detail.
later in this users’ guide, but a normal rule-of-thumb is that the clearance between the sleeve and the tip should not exceed 0.004 inches.

However, alignment between the tip and sleeve is normally measured at room temperature, but pouring of the liquid metal and then forcing it through the sleeve will distort the shape of the sleeve during operation at elevated temperatures. In addition, the tip will heat and cool during use, and so its diameter will be constantly changing. This distortion can cause tip stalling, and tip wear, and can result in inconsistent injection profiles\(^{(16)}\).

This section of the users’ guide will consider the temperature profile within the sleeve, describe how this can distort the shape of the sleeve, and examine methods that can be used to reduce temperature differences and so minimize distortion and shape changes of the sleeve.

The temperature profile shown in Figure 9 will produce distortion of the sleeve, and three separate types of distortion can occur:

a) As the bottom of the sleeve is hotter than the top, distortion along the length of the sleeve tends to produce the banana-type distortion shown in Figure 17.

b) The inside bore of the sleeve will also become out-of-round, and the magnitude of the distortion of the bore has been simulated for three positions in the sleeve as shown in Figure 18.

c) As shown in Figure 9, the biscuit end of the sleeve is the hottest, and the highest intensification pressure levels are also applied at this location. Therefore, shot sleeve distortion also tends to be high at this position.

Chang et al\(^{(17)}\) have performed simulations to determine the impact of die casting process parameters on distortion of a shot sleeve. Their calculations were performed for a sleeve 340 mm (13.4 ins) long, 200 mm (7.9 ins) outer diameter, 116 mm (4.6 ins) inner diameter, fed with liquid metal at 650°C (1200°F) with a sleeve fill percent of 50%, and a dwell time in the sleeve of 4.0 seconds. As demonstrated in Figure 19, the sleeve distortion increases with an increase in the molten metal temperature, an increase in the dwell time, and an increase in the fill percent. Conversely, the sleeve distortion decreases with an increase in sleeve preheat temperature, an increase in sleeve length, and an increase in the outer diameter (i.e., wall thickness).

---

**Figure 17:** Distortion of the sleeve caused by differential heating\(^{(7)}\)

**Figure 18:** Simulation showing the magnitude of the distortion of the bore of a shot sleeve over a 10 cycle run\(^{(5)}\)

**Figure 19:** Impact of process parameters on the magnitude of distortions in shot sleeves\(^{(17)}\)

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The initial temperature of the molten metal (°C)

- Initial temperature of the molten metal
- Sleeve length
- Dwell time in the sleeve
- Outer diameter of the sleeve (wall thickness)
The solution to minimizing sleeve distortion is to utilize cooling (or heating) to control the sleeve temperature. As noted earlier, some sleeves are fabricated with copper sleeves to better distribute the heat within the sleeve. Another simple option is to place a water jacket around the outside of the sleeve, underneath the pouring hole (Figure 20). A more active approach to controlling temperature is to machine grooves in the outside wall of the sleeve, and insert copper cooling tubing into the grooves. Robbins and Singh suggest the use of an “M-shaped” loop that extends up the sidewalls of the sleeve (Figure 21). Probably the best option is to gun drill holes into the walls of the sleeve, connected by cross holes (Figure 22). This allows the cooling liquid (water or oil) to directly cool the sleeve. More information about using cooling and/or preheating to for thermal management and distortion control is presented later in this users’ guide in Section 2 on Thermal Management.

**The Plunger Tip**

The plunger tip (or shot tip, as it is sometime called) is activated by the shot cylinder and pushes the liquid metal through the shot sleeve into the die cavity. Common designs of one piece shot tips are shown in Figure 23. Clearly the design of one-piece plunger tips has not changed much in the past 50 years or so, as Figure 24 shows a sketch for a plunger tip published in 1962 that looks very similar to the design of modern tips.
The front face of the plunger tip will obviously be heated as it moves forward through the shot sleeve to inject the liquid metal into the cavity. This heating will be especially severe during the intensification phase of the injection cycle. If not controlled, the heating will cause rapid expansion of the front face of the tip, causing the tip to seize within the sleeve. This seizing can prevent the transferring of the intensification pressure from the shot cylinder to the liquid metal (resulting in excessive porosity in the castings), and in the extreme case will prevent the piston from moving as the casting is ejected from the die, likely causing bending of the casting. Therefore, this heating of the plunger tip has to be carefully controlled, and this is achieved through careful choice of materials to fabricate the tip, and from internal cooling of the tip. These are described in more detail in the following sections.

### Materials

Today plunger tips are produced from a range of materials, including cast irons, steels, beryllium-copper and other copper alloys. In North America, plunger tips are commonly produced from beryllium copper alloys, although steel is also used (especially in the multi-piece tip designs described later in this section). In Europe, tips are commonly fabricated from beryllium-free high strength copper alloys, due to the health issues related to beryllium. In Asia, cast iron tips still appear to be common.

Beryllium-copper alloys have an excellent combination of high strength and high thermal conductivity. Table 3 lists the chemical composition and properties of copper-beryllium alloys commonly used for shot tips. As the beryllium content of the tip alloys increases, the strength increases but thermal conductivity decreases. It is also worthwhile stating that care should be employed when machining or grinding copper-beryllium tips, to prevent the formation of harmful fine dusts. Appropriate safety procedures need to be established and followed.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Be</th>
<th>Co</th>
<th>Ni</th>
<th>Si</th>
<th>Cu</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>0.35-0.80</td>
<td>--</td>
<td>1.0-2.0</td>
<td>Bal</td>
<td>183</td>
<td>High conductivity, good strength and good high temperature properties</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.9-2.25</td>
<td>0.35-0.70</td>
<td>--</td>
<td>0.20-0.35</td>
<td>Bal</td>
<td>130</td>
<td>High strength, hardness, wear resistance</td>
</tr>
</tbody>
</table>

Steels are also used for the fabrication of plunger tips. The strength of the types of tool steels used for the fabrication of plunger tips is significantly higher than beryllium copper, so the walls of the tips can be thinner. However, the thermal conductivity of tool steel is significantly lower than that of beryllium-copper, and so manufacturers of steel tips often use more complex cooling schemes for the cooling of steel tips. For example, Figure 25 shows a photograph of a one-piece steel tip where complex-shaped internal cooling channels have been configured to optimize cooling.

![Figure 25: Steel plunger tip](image)

Multi-piece tips are typically fabricated from both copper alloys and steels. Two examples are shown in Figure 26. Typically, the steel is used to provide strength to support the copper, while the copper-alloy is used to optimize heat extraction and cooling.
As noted earlier, cast iron tips are common in Asia. These have lower strength than competing materials, and the number of shots that can be produced before replacement appears to be significantly lower. However, as the cast iron tips also have lower fabrication costs, this offsets their shorter lives.

Finally, as shown in Figure 27, replaceable rings fabricated from copper alloys or steels are also used with plunger tips. The rings, which are split for ease of installation, are mounted on the front of the tip and automatically adjust to the inside diameter of the sleeve (Figure 27b), thereby reducing flash between the tip and the sleeve. As the gap between the sleeve and the tip is essentially eliminated (so long as good thermal control is maintained), this can provide the sealing necessary for vacuum die casting. Replacement of the rings is also easier and lower cost than having to replace the entire tip.

Tip Cooling

As noted earlier, cooling of the plunger tip is extremely important, to control the expansion of the tip caused by heating, to prevent it from seizing in the shot sleeve. Normally the tip is cooled via a copper rod inserted through the center of the plunger rod (shown in Figure 28). For the simple tip designs shown in Figure 28, this copper cooling rod shoots the cooling water at the back face of the tip, and the water is then evacuated through the plunger rod. In one of the current authors’ experiences, for optimum cooling it is important that the front end of the copper cooling rod be located close (about ¼-inch) behind the back-face of the copper tip.

Alternate more complex cooling systems are suggested for multi-piece tips. One such system shown in Figure 29 feeds the water to the tip through the center of the plunger rod, through the holder and directly to the inside face of the plunger tip. The water is then distributed through four channels to the circular external coolant channel. These channels are designed to create a turbulent flow to maximize heat transfer. The water then escapes through holes in the steel plunger holder and is evacuated through the plunger rod.

The Shot Cylinder

The shot cylinder provides the power to inject the molten metal into the die cavity. High performance injection systems are now available which provide shot speeds up to 400 inches per second when needed. The shot cylinder is supported by a C-frame (or similar mechanism), which allows for a stable shot end during injection. The technical specifications of the shot cylinder are not a topic of this users’ guide, but technical information is available from NADCA on the design, specification, use and maintenance of shot cylinders. NADCA Course #EC-407, “Mechanical Maintenance” and its corresponding text, as well as NADCA Course #EC-420, “Die Casting Machine Systems” and its text, provide comprehensive information on shot systems, including shot cylinders.

For the purpose of this discussion on shot systems, the primary concern about the shot cylinder is alignment. Shot alignment refers to the alignment between the center line of the shot cylinder rod with the center line of the platen shot hole and shot sleeve. If the two center lines are not lined up, the shot tip will advance through the shot sleeve on an angle that can cause uneven wear on the shot tip and shot sleeve. The shot cylinder must be realigned if the center lines are too far off.
The alignment can be checked by inserting a fixture into the platen that will center itself on the sleeve bore and will translate itself along the center line of that bore. New laser alignment gauges, similar to the one shown in Figure 30, can be centered along the same line. The alignment of the platen sleeve bore center line should be checked and recorded throughout the stroke of the shot cylinder rod so that the correction can be made to the shot cylinder. The shot cylinder must also be properly supported so that the alignment of the shot cylinder to the shot sleeve is correct throughout the stroke of the shot cylinder while under high hydraulic pressure.

Many times when die casters are having problems with shot tip life, sleeve life and maintaining consistent part quality, the cause is that they do not have an adequate flow of cooling water to the plunger tip. The plunger rod often needs to be improved in the following three areas:

**Water line fittings** - Often the NTP fittings on the shot rod are not big enough to allow sufficient flow of water. Sometimes a die caster will have a ¼-inch NTP pipe fitting on the water input and/or output to the rod. Usually this is inadequate. It should be increased to ½-inch or ¾-inch whenever possible.

**Water tube diameter** - Sometimes the bubbler tube is too small to allow the necessary water flow through the rod and tip. The standard ¼-inch or ½-inch tube may not be adequate. The flow on the exit side of the plunger rod should be checked with a flow meter or simply with a bucket and a watch. Some die casters have a flow meter permanently connected to a solenoid which will stop the machine if the rate of flow drops below a preset level.

**Diameter of the hole in the shot rod** - The center hole in the plunger rod must be large enough to allow the cooling water to exit without additional back pressure. The diameter of the return hole must, of course, be equal to or greater than the ID of the tube. Sometimes the die caster will have a properly sized tube and return hole in the plunger rod, but will mount the tip to the rod with an adapter. Be sure that the adapter also has an adequate hole - otherwise, back pressure will reduce the water flow.

Table 4 shows recommended water flow rates for multi-part plunger tips. McClinic\(^\text{26}\) suggests even higher flow rates for conventional tips, recommending that for a 3-inch diameter tip, a minimum flow rate of 5 gallons per minute be used. To ensure consistent operation of the plunger system, it is essential that the water flow rates be monitored, unless excessive heating of the tip will occur, resulting in the tip dragging in the sleeve, likely damaging both tip and sleeve.

<table>
<thead>
<tr>
<th>Tip Diameter (inches)</th>
<th>Required Flow Rate (gals/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 to 2.5</td>
<td>2.5 to 3.5</td>
</tr>
<tr>
<td>2.5 to 4.0</td>
<td>3.5 to 5.0</td>
</tr>
<tr>
<td>4.0 to 5.75</td>
<td>5.0 to 6.5</td>
</tr>
<tr>
<td>5.75 to 7.0</td>
<td>7.0 to 9.0</td>
</tr>
</tbody>
</table>

**Table 4: Flow rate for tip cooling**

It is worth noting that, with respect to cooling of the tip, the temperature of the cooling water is not as important as the rate of flow. As the rate of flow is increased, the removal of heat energy is greater than when the flow is constant and the temperature of the coolant is reduced. Strictly from a cooling perspective, therefore, it is better for the die caster to increase the volume of water through the shot rod than to try to lower the temperature of the cooling water. It is very important that the flow of cooling water through the plunger rod and shot tip be carefully and effectively managed.
In the previous section, the various components of the injection system, including the shot sleeve, plunger tip and plunger rod were discussed. The design of these individual components is fairly straight-forward and there are a number of competent suppliers to assist the die caster with that task. In practice, however, these components must operate together as a reliable injection system, which is a critical part of the die casting process. In this section, several key issues that die casters must address every day to be successful are presented - alignment, lubrication, and thermal management. It is important to recognize that each of the injection system components affects the operation of other components and they must be operated as a system.

**Alignment**

As noted earlier, it is essential that the clearance between the shot sleeve and plunger tip be correct, and that the sleeve and tip be correctly aligned. Published recommendations for clearance between an H13 steel sleeve and a copper-beryllium plunger tip vary slightly – for example Kelm suggests 0.001-inches of clearance per each inch internal diameter of the sleeve\(^{(9)}\), while Sobol et al\(^{(4)}\) suggest a clearance of 0.003 inches for any tip diameter smaller than two inches and an additional 0.001 inch for every inch over two inches (e.g., for a 2½ inch tip the clearance would be 0.0035 inches). However, Robbins & Singh also suggest that the total clearance not exceed 0.004 inches\(^{(10)}\). If the clearance is too small, the tip can seize in the sleeve as it expands during operation. If the clearance is too large, the liquid metal can blow-back past the tip, and this extra thickness of flashed metal can also result in seizing of the tip. In either case, the seizing interrupts the normal operation of the tip, and can negatively impact both the injection profile and the intensification pressure.

Careful alignment between sleeve and tip are also very important, unless the shot tip will advance through the shot sleeve on an angle that can cause uneven wear to the shot tip and shot sleeve\(^{(4)}\). As noted earlier, when considering shot sleeve alignment, the crucial factor is the alignment between the center line of the shot cylinder rod with the center line of the platen shot hole or the shot sleeve. If the two center lines are not lined up, excessive wear of tip and/or sleeve will occur.

McClintic\(^{(1)}\) reports that for machines that have an adjustable shot location, it is crucial that the C-frame or yoke be correctly installed and supported, and that alignment shims or dowels be installed. The shot sleeve must also be correctly aligned within the platen. McClintic also suggests that the shot cylinder rod needs to be checked in both the extended and retracted positions, as excessive droop indicates that either a worn cylinder rod bushing and/or shot cylinder piston and cylinder need repair.

Another factor that can lead to bad alignment between the tip and the sleeve is the linkage of the shot rod to the shot cylinder rod. The shot rod usually screws into the rear of the tip and is held to the end of the shot cylinder rod by a shot rod coupler. If the shot rod is bent, the tip will be angled and cause excessive wear. If there is too much play in the shot rod coupler, the center line of the shot cylinder rod will not coincide with the center line of the shot arm, and gravity will pull the rear of the shot arm down, causing the tip to be angled. Sobol et al\(^{(10)}\) recommends that a maximum of 0.020 inch should be used as the coupler clearance and as the maximum misalignment between the shot rod and shot cylinder rod.

Obviously, to ensure alignment, it is also critical that the shot sleeve be accurately machined. To minimize wear as the plunger moves backwards and forwards, it is important the sleeve be round and straight (within ±0.001 inches), and that the internal bore be concentric with the outside diameter (to within 0.005 inches TIR)\(^{(3,4)}\). McClintic\(^{(1)}\) indicates that the plunger should move smoothly through the shot sleeve by hand, and he suggests that this can easily be checked by standing the shot sleeve upright on the floor, sealing the bottom with a smooth piece of metal, and dropping the plunger through the sleeve. McClintic indicates that if the sleeve-tip clearance is correct, the tip will slow down as it approaches the bottom of the sleeve due to trapped air, but if the clearance is too large, it will drop like a rock. Too little clearance will result in jamming of the plunger.

McClintic\(^{(1)}\) also advises that the parting line of the sleeve be checked, as it can become peened or coined during use (see Figure 32). This can be caused by the use of excessive locking force, especially as the sleeve can become longer due expansion from heating. To minimize this problem, McClintic\(^{(1)}\) suggests a chamfer or radius be placed on the die end inside diameter of the sleeve (Figure 32). Sobol et al\(^{(10)}\) suggest that the sleeve be fabricated so that when it is cold it sits 0.010-inches behind the parting line, providing room for expansion as it heats.
Shot Sleeve Lubrication

Introduction

Midson\(^{(27)}\) classified the various plunger lubricants used in the die casting industry into the following four classes:

- Oil-based
- Water-based
- Granules or dry pellets
- Powder

In the past, oil-based plunger lubricants were the most commonly used. However, excess lubricant would often to drip onto the floor and collect under the shot sleeve, mixing with any liquid aluminum overflowing from the pour hole, and the heat from any liquid aluminum overflowing the sleeve during ladling could ignite this excess oil, producing a small fire and large amounts of smoke. To alleviate these problems with oil-based plunger lubricants, the lubricant manufacturers developed alternative lubrication concepts, such as water-based, granules and powders. These are each briefly described below.

- According to Sdregas\(^{(28)}\), oil-based plunger lubricants have historically consisted of a mixture of heavy mineral oils (70-90%), tackiness additive (2-10%), solid lubricant dispersions such as graphite (2-10%), and vegetable oils (2-10%). The oil-based lubricants come in two varieties, clear or filled. The filled lubricants contain a suspension of solid lubricating particles, such as graphite, molybdenum disulfide or boron nitride.

- Water-based plunger lubricants have the advantage of producing no flames when the liquid metal is poured into the shot sleeve. Water-based lubricants are essentially an emulsion of the lubricant in water, and the concentrate received from the manufacturer is often further dissolved with water prior to use. Typically dilution ratios used with water-based plunger lubricants are lower than used for die release agents – with plunger lubricants the maximum dilution ratio is typically about 6:1.

- Granules, or dry pellets, were introduced in the early 1990s to solve the housekeeping and cleanliness issues experience with the oil-based plunger lubricants\(^{(29)}\). The pellets are typically manufactured from wax compounds along with extreme pressure additives, and pellets can also contain additions of graphite particles (as much as 40% graphite, although 5-10% is more typical). Generally the pellets range in size from 0.010 – 0.020 inch on the low end to 1/32 – 1/16 (0.031-0.063) inch on the larger end.

- Powders have many of the same advantages in housekeeping and cleanliness as reported for dry pellets. Due to their fine nature, powders are often more difficult to apply. For example, they should be added after die spray (as the air blast can blow away powder) and after the die closes, but before metal ladled. Teresi\(^{(30)}\) also notes that, if the tube used to feed the powder to the shot sleeve is far away from pour hole, then much of the powder can be lost (with only about 50% being applied). Teresi’s rule of thumb is that there should be no more than 3-three inches from the end of feed tube to the pour hole.

Shot Sleeve Lubrication Systems

Kraklau\(^{(31)}\) provides an excellent review of seven different methods available for lubricating the shot sleeve, and summaries from his analysis are provided below.

The brush on method, shown in Figure 33, merely involves using a brush to apply the lubricant directly to the tip. It is very simple and easy to use, but its disadvantages include the fact that it is generally messy, inconsistent and very dependent upon the operator. In addition, this technique provides little in terms of sleeve cooling.

Figure 33: Brush on method\(^{(31)}\)
A solid granular dispenser is shown in Figure 34. This applies granules of lubricant directly to the sleeve through the pour hole. A similar process can also be used for powder lubricants. With this process it is easy to control the amount of lubricant applied, does not have problems with dripping, and minimizes the amount of smoke generated. However, the automated units are more costly to purchase, the granulated lubricants can generate excess porosity within the castings, and they may stain the castings’ surfaces. This technique also does little in terms of cooling the sleeve.

Figure 34: Solid granular dispenser

An automated system is also available for dripping liquid lubricant through the pour hole (Figure 35). This approach is again more consistent than the brush method, as it is not dependent the operator, and also will impact cycle time. However, similar to the brush method, this system can be messy, and again does not cool the sleeve.

Figure 35: Drip lubrication system

The O-ring groove approach is very similar to drip system, but tends to do a better job of lubrication (Figure 36). This process is not as messy as either the brush or dripping methods, but operational costs are greater, as each sleeve (or tip) needs to have O-ring grooves installed. Again, this approach does little for cooling the sleeve.

Figure 36: O-ring groove system

The system for using air pressure to spray lubricant into the shot sleeve (Figure 37) is not as good for lubricating the tip, but does a better job of cooling the sleeve. It tends to get more lubricant forward of the pour hole, and also provides less part discoloration than solid lubricant systems. Two main disadvantages include its tendency to produce smoke, and if it is applied too heavily can produce porosity within the castings.

Figure 37: Pressure spray into the shot sleeve

Another approach involves using a reciprocating spray to blow the lubricant into the sleeve from the parting line end, and while it tends to do a good job of cooling the die end of sleeve, it does little or no cooling at the pour hole end (Figure 38). This system can be a good supplementary system to a main plunger lubricant system. Generally, it is recommended to use a different plunger lubricant than used with the main die spray.

Figure 38: Reciprocating spray

A plunger rod spraying system sprays a water soluble lubricant through the plunger rod on the shot return stroke (Figure 39). This approach will cool and lubricate the entire sleeve, and
will also cool and lubricate the tip. Kraklau\(^{(31)}\) suggests that this is the best all-around system, and Brown et al\(^{(32)}\) reported using it for high vacuum die casting. Drawbacks include having to pay more for plunger rods, along with the cost of the applicator. This system is also limited to thinner weight lubricants.

**Figure 39: Plunger rod spraying\(^{(31)}\)**

**Other Comments**

Teresi\(^{(30)}\) recommends that applicators for powder or granule shot lubricants should not be mounted directly to the stationary platen. The platen can get very hot and may damage components, and may also melt the lubricants. He suggests that it is necessary to mount the applicator to platen, a mounting plate with spacers should be used that can keep the applicator at least two inches from the platen.

**Thermal Management**

As noted earlier, one of the most critical interactions involved in cold chamber die casting is between the shot sleeve and shot tip. Adequate operating clearance must be maintained to permit smooth motion of the injection system, but with small enough clearance to prohibit liquid metal from bypassing the shot tip and exiting the rear of the shot sleeve. Generally die casters consider that the maximum gap that can exist between the plunger tip and the shot sleeve during the casting process is 0.004 inches. If at any time during the shot, the gap exceeds 0.004 inches, the alloy is likely to penetrate the gap and flash or blowby will occur.

If both the shot sleeve and the plunger tip remained at a constant temperature, there would be no problem in maintaining a consistent gap between the sleeve and the tip. If the ID of the shot sleeve is no greater than about three inches, the problems relating to thermal management are often considered minimal. However, a similar temperature increase will cause a six-inch diameter sleeve to expand twice as much as a three-inch sleeve, but unfortunately the maximum allowable gap of four thousandths of an inch remains unchanged.

The amount by which each metal will expand or contract with changes in temperature \(\Delta T\) is expressed in terms of its “Coefficient of Thermal Expansion” (CTE). As noted earlier, plunger tips are commonly made of beryllium-copper and shot sleeves are made of H13 steel. The coefficient of thermal expansion for beryllium-copper is 0.0000094/°F (9.4 x 10\(^{-6}\)/°F), but for H13 it is lower, being 0.0000061/°F (6.1 x 10\(^{-6}\)/°F). Table 5 shows actual operating temperatures and calculated clearances from a casting machine using a conventional plunger of beryllium copper and a shot sleeve of H13. The machine was set up at 70°F with a clearance of 0.005 inches between the sleeve and tip.

<table>
<thead>
<tr>
<th>Position</th>
<th>Item</th>
<th>Temperature (°F)</th>
<th>Dimension (inches)</th>
<th>Clearance (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>During Set-Up</td>
<td>Sleeve</td>
<td>70</td>
<td>5.000</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Tip</td>
<td>70</td>
<td>4.995</td>
<td></td>
</tr>
<tr>
<td>At pour hole end (while casting)</td>
<td>Sleeve</td>
<td>570</td>
<td>5.015</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Tip</td>
<td>120</td>
<td>4.997</td>
<td></td>
</tr>
<tr>
<td>At die end (while casting)</td>
<td>Sleeve</td>
<td>390</td>
<td>5.010</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Tip</td>
<td>290</td>
<td>5.010</td>
<td></td>
</tr>
</tbody>
</table>

**Table 5: Impact of operating temperatures on the tip-sleeve clearance**

For the operating temperature shown in Table 5, at the pour end the sleeve expanded by 0.0155 inches and the plunger by only 0.0025 inches. Therefore, the clearance increased to 0.018 inches and flashing is probable. At the die end, the sleeve contracted slightly, but the plunger expanded so much that the clearance disappeared and there is now a danger of the plunger seizing. The solution to this problem is to control the operating temperatures of both the plunger tip and the shot sleeve much closer than the values shown in Table 5.

Another consideration for shot sleeve cooling is that the alloy being poured into the sleeve is at about 1300°F, while the annealing temperature of H13, the usual shot sleeve material, is only 1085°F. If the shot sleeve is not adequately cooled, it will likely lose some of its hardness. Soon, wear will result from the abrasive action of any alloy that penetrates the gap between the sleeve and tip.

To minimize the temperature changes shown in Table 5, die casters usually control the temperature of shot tips and shot sleeve via with water cooling or oil heating/cooling. Nearly all die casters cool their plunger tips. It is worth noting that the most common cause of excessive shot tip expansion and wear is insufficient cooling, and even experienced die casters sometimes neglect this. The rate of water flow is easily determined, and should be monitored constantly. Recommended flow ranges needed for cooling tips of various sizes are discussed in Section 1- “The Plunger Rod” of this users’ guide.

Once the die caster has reduced the thermal expansion of the shot tip, attention can then be focused on controlling the operating temperatures of the shot sleeve. Different methods of controlling sleeve temperatures are discussed in Section 1- “The Shot Sleeve” of this users’ guide.

A common misconception, however, is that the amount of thermal expansion of a shot sleeve is simply a factor of its diameter and its maximum temperature. If this were the case, temperature control would simply depend on cooling, but this is incorrect. The amount of thermal expansion or contraction depends on the ID of the sleeve, and the amount of temperature change, up or down, not on the maximum temperature. This temperature differential, usually referred to as \(\Delta T\), will cause exactly the same amount of expansion at any point on the temperature scale. Therefore, one approach often ignored by die casters is that by preheating the shot sleeve with hot oil, the amount of tip and sleeve wear which normally occurs while the sleeve is heating up to operating temperatures can be minimized. If needed, the oil can be distributed at both the pour hole end and at the die end of the sleeve, to balance the temperature through-
out the sleeve. Experience has shown that sleeves thermally controlled with oil can last an average of 300% longer than standard sleeves. From the consistency of the temperatures, top and bottom and back to front, it is more likely that these sleeves remain round and straight. One provider of sleeves that were thermally controlled with oil reported the types of increases in tip life listed in Table 6.

<table>
<thead>
<tr>
<th>Caster #1</th>
<th>Caster #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tip Diameter</td>
<td>4.75 inches</td>
</tr>
<tr>
<td>Previous Tip Life (shots)</td>
<td>4,000-6,000</td>
</tr>
<tr>
<td>Sleeve thermally controlled with oil</td>
<td>YES</td>
</tr>
<tr>
<td>Average Life of New Tip</td>
<td>27,500 shots</td>
</tr>
<tr>
<td>Increase in Life</td>
<td>450%</td>
</tr>
</tbody>
</table>

Table 6: Impact on tip life of using hot oil to control shot sleeve temperature

So, for example, if a shot sleeve has been preheated by circulating hot oil at 400°F, ΔT will be reduced, as well as the total amount of expansion. Also, as the pour continues, sleeve temperature increases above 400°F will be minimized, as the oil will then act as a coolant. When oil is used to preheat the sleeve, the temperature variation, both top to bottom and back to front, can be very closely controlled, minimizing expansion. The four thousandths of an inch maximum gap can be maintained and even improved. With proper thermal control, many die casters are able to operate their tips and sleeves by using a clearance of 0.001 inches (measured at room temperature).
Chapter 3

Industry Examples

To provide an idea of what can be expected with the correct application of shot system components, some industry examples are provided in this section. The examples are from suppliers of shot tips and shot sleeves using different design approaches. It should be emphasized that there is no “magic pill” when it comes to shot system components. The components must work together to meet the requirements of the process being implemented, and a systems approach must be utilized when considering modifications to a specific component. The die casting process is a complex and dynamic environment and die casters looking to change one thing, such as a new tip, who are expecting to see dramatic differences, will probably be disappointed.

Example #1

In this case, the die caster used two-piece shot sleeves – one piece for the platen end of the machine that interlocked with a second piece in the cover half of the die. Typically, this customer had trouble achieving greater than 5,000 shots per tip before the tip required changing. The tip was typically changed when it was bypassing metal and not due to some other criteria. The die caster had experimented with a steel tip that was coated with a high hardness spray weld. These tips often stuck in the sleeve and they could not equal the life that had been achieved with beryllium-copper tips. After examining the overall shot end design, a thermal controlled shot system was tested, which incorporated the same two-piece sleeve design but with thermal control, a new plunger rod, and a steel piston. After a lengthy testing cycle, the results showed an average tip life of over 60,000 shots. This was a dramatic improvement, but success was not the result of just changing the type of shot tip. It was the result of the design and implementation of the tip, sleeve and plunger rod specifically for the machine, die and casting process being used by that customer.

Example #2

Another similar example involved a large manufacturer of small engines. In order to help control the escalating costs for shot end tooling and to combat the negative effect on productivity, the manufacturer came to the shot tip supplier for solutions. In this case, more changes were necessary than just changing the tip and sleeve. In fact, the die and platen adaptor had to be bored to permit greater wall thickness for the sleeve. Many die casters now seem to need more and more metal velocity to make a high quality casting. However, they often do not change anything other than the ID of the sleeve.

Example #3

For acceptable productivity, the plunger tip must pass through the shot sleeve quickly and smoothly. This can only happen if the shot sleeve is round and straight, and also if the gap between the plunger tip and the sleeve always remains less than four thousandths of an inch. The problem is that when heated, metal expands, and a copper plunger tip expands at a much greater rate than the steel shot sleeve. In this example, the solution to the problem was to automatically control the temperature of the shot sleeve, thus making its ID more consistent during the shot. In addition, the die casting changed tips to a design that included the steel rings shown in Figure 27. The casters were able to obtain improvements in tip life of between 350% and 500%.

Example #4

In another documented example, one-half million dollars per year was the estimated savings on shot end components after a major automotive die caster converted its 40 aluminum die casting machines to a new shot system. The new system reduced average annual downtime for one machine by 8,700 minutes. The dramatic cost reduction resulted from reducing the frequency of plunger component replacement and the time required for maintenance. Instead of a beryllium-copper plunger tip in direct
contact with the bore of the shot sleeve, the new plunger tip combines a forged beryllium copper tip with steel rings. Down-time for replacement changed from 10 minutes to 2 minutes. The average life of the standard beryllium-copper tips at the automotive caster was 800 shots for a 2½ inch OD tip. The rings on the new plunger tip design averaged 25,000 to 35,000 shots, with the tip itself needing replacement after 100,000 shots, generally due to heat checking.

There is now experience with the ring tips in many die casting machines in North America. One plant in Canada calculated that an increase of 7,700 shots for one machine for one month resulted in a six-figure sales increase. At an Ohio die casting plant, consumption of tips had been from 200 to 240 per month. After conversion to the new system, tip usage declined to only 40 rings and 3 tips per month.
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